Reservoir Monitoring Consortium (RMC)

Annual Project Review Meeting

CO$_2$ EOR Reservoir Workflow

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CO$_2$ EOR

• Considered the ‘best’ choice of EOR (vs. Chemical methods) for High Temperature & Salinity Carbonates
  – High Reservoir Pressure
  – Favorable Mobility
  – Shortage of HC gas for miscible injection
  – Issues with N2 Injection (high Miscibility pressures, cost and CO$_2$ emission)

• Main Considerations:
  – Availability & Cost
  – Vertical & Areal Sweep
  – Wells and Facilities
  – HSE
Middle East Applications

- Pilot Studies
- CO$_2$ EOR Reservoir Screening done by ADCO
- Rumaitha CO$_2$ EOR Pilot Results
- BAB CO$_2$ EOR Pilot
- Aramco CO$_2$ EOR Pilot
- In design stage for other reservoirs
Recent Publications


3) **Lessons Learned from the First Miscible CO$_2$-EOR Pilot Project in Heterogeneous Carbonate Oil Reservoir in Abu Dhabi, UAE**, A. Al Basry, S. Al Hajeri, H. Saadawi, F. Al Aryani, A. Obeidi, S. Negahban, G. Al Yafei, Abu Dhabi Company for Onshore Oil Operations (ADCO)

4) **EOR Potential in the Middle East: Current and Future Trends**, Saad M. Al-Mutairi, SPE and Sunil L. Kokal, SPE, Saudi Aramco
Pilot Objectives

• Evaluate EOR Potential (Ultimate Recovery)
• Recovery of ‘Difficult Oil’ (low, heterogeneous permeability)
• Reduce the uncertainty with EOR Performance prediction (Production, Recovery)
• Efficient use of CO₂
**Example of Evaluation Criteria**

<table>
<thead>
<tr>
<th>Evaluation criterion</th>
<th>Description</th>
<th>Design consideration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweep efficiency</td>
<td>On a relative basis, how well is the pilot concept expected to improve sweep efficiency over the existing development plan?</td>
<td>EOR potential / difficult oil</td>
</tr>
<tr>
<td>Interpretability</td>
<td>Will results from the pilot concept be able to be interpreted?</td>
<td>EOR potential / performance prediction</td>
</tr>
<tr>
<td>Scalability</td>
<td>On a relative basis, how easy will it be to scale up the pilot concept (from a subsurface perspective) to full-field?</td>
<td>Future phasing</td>
</tr>
<tr>
<td>CO₂ containment</td>
<td>Will the pilot concept limit CO₂ movement out of pattern (horizontally and vertically)?</td>
<td>EOR potential / “do no harm” to existing facilities</td>
</tr>
<tr>
<td>Cost</td>
<td>On a relative basis, what investment in wells and completions is required to implement the pilot concept?</td>
<td>Future phasing</td>
</tr>
<tr>
<td>Operational complexity</td>
<td>On a relative basis, how difficult will it be to successfully execute and operate the pilot?</td>
<td>Execution</td>
</tr>
<tr>
<td>Flexibility</td>
<td>On a relative basis, how will operational problems impact the ability of the pilot to achieve its objectives?</td>
<td>EOR potential / execution / CO₂ utilization</td>
</tr>
</tbody>
</table>

* Ref 1. in Slide 4
Monte Carlo Simulations

1. Define HM tolerances
2. Run simulations from $t=0$ through to end of prediction
3. Develop equations describing HM error and pilot performance responses
4. Run Monte Carlo simulations on the equations
5. Filter out MC simulations that do not meet HM error tolerances
6. Use surviving MC simulations to develop exceedence curves that quantify expected pilot performance range

* Ref 1.
Pilot Production Performance Ranges

CO$_2$-EOR Pilot Production Performance Ranges
Thamama Zone B

*Ref 1
CO₂ Injection/Production Zones

* Ref 2
Pilot Results*

- CO₂ breakthrough occurred faster than expected (based on surface metering with CO₂ analyzers).
- C/O Logging showed CO₂ advance within the high-perm streak in the reservoir.
  - High resolution simulations also confirmed the CO₂ breakthrough
- No main issues with injectivity, asphaltene deposition.
- Large negative skin in injector indicating possible induced fracture
- CO₂ jet impacted one of the tubulars at the producer.
- X-Well Seismic did not perform as expected.

* Ref 2
Miscible Injection
Line drive with vertical injectors and producers
OH Observation Well(s)
First inject water before CO$_2$ and determine Residual and Remaining Oil
6 months of CO$_2$ injection followed by 6 months of water injection
Monitor Change in Oil Saturation after CO$_2$ flood
Simulations show gravity override of injected CO$_2$ into top zones
Overall Assessment of the CO$_2$ Pilot

+ Appropriate well spacing inline with field implementation
+ Vertical wells for accurate reservoir description and control (as opposed to horizontal injectors / producers)
+ Continuous Seismic Monitoring as well as X-Well Seismic & EM measurements for Saturation Monitoring
- Passive Pilot without Control
  - No mechanical control in injectors and producers
  - No sandface pressure measurements
- OH Observation Wells could be problematic from the saturation monitoring point of view (crossflow of CO$_2$ between different reservoir zones)
Lessons Learned

• Pilot dimensions should be in line with key objectives of the pilot (neither too small nor too large)
• ‘Active’ Pilot instead of ‘passive’ information gathering
• Wells & Completions that are in line with field implementation
  – Mechanical Controls & Chemical Methods
• Need for Robust Measurements for Monitoring
  – Inter-Well (2D or 3D) Saturation measurements that can resolve various phases: Oil, Water and Miscible Agents (EM, Seismic, Gravity, Pressure, etc.)
  – Distributed Pressure / Temperature Measurements sensing the formation (rather than the wellbore)
Research Focus

• Reservoir Workflow: Data Integration and Fast Feedback loop for Optimum Displacement & Oil Recovery:
  – Incorporate both discrete and continuous measurements (Seismic, EM, Pressure...)
  – Reduce Uncertainty with multiple realizations

• Benefits:
  – Early detection of Reservoir Risks (gravity override, early breakthrough of injected agents, etc.)
  – Mitigation vis-à-vis Controls in-place (both mechanical & chemical methods)
Challenges

• Computation Time:
  – High Resolution Reservoir models (thief zones, fractures, flow barriers)
  – Large Number of Cases due to Uncertainty (vertical communication, reservoir contrasts, fracture corridors, etc.)

• Measurement Sensitivities:
  – Multi-Phase displacements: Supercritical CO$_2$, Water and Oil

• Inversion:
  – Deterministic approach: applicable to limited cases
  – Stochastic approach: Not very practical in many field applications
  – Heuristic Methods combining these two